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ORNL D-Li Fusion Neutron Facility

Accelerator Systems Cost Report

September 1, 2019

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1.0 EXECUTIVE SUMMARY

Several past design studies were reviewed and an analysis of alternatives completed to assess the range of accelerator parameters and accelerating structure types that can potentially meet the requirements of a 125-mA, 40-MeV, D-Li Fusion Neutron Facility. The design studies reviewed included past LANL designs for IFMIF and designs based on the use of modified versions of the LANL LEDA. Also reviewed were the past IFMIF-EVEDA design iterations that explored several options for the main linac including the use of an Alvarez DTL, interdigital accelerating structures, and a superconducting RF half-wave resonator {SCRF HWR) based main linac. Results of the analysis of alternatives were used to develop two options for consideration based on a common set of accelerator system parameters:

- Ion Source and Injector – 140 mA D^+, DC/CW operation (pulsed capability for tuning), 100 keV, transverse output emittance <0.25 π-mm-mrad.
- Low-Energy Beam Transport (LEBT) – 2 solenoid, gas neutralization, electron trap
- RFQ – 100 keV to 5 MeV, 125 mA CW
- Medium-Energy Beam Transport (MEBT) – 4-5quadrupoles, 2 multi-gap buncher cavities
- Main Linac – 5 MeV to 40 MeV, 125 mA CW (superconducting or normal conducting)
- High-Energy Beam Transport (includes beam expander optics) – quadrupole magnet focusing lattice for beam transport, multipole magnets for beam expansion and 2D uniform distribution, final configuration TBD based on Li target geometry.

Option 1 reproduces the 40-MeV IFMIF-EVEDA-LIPAc design based on an RFQ and a SCRF HWR-based main linac. Option 2 is an alternative 40-MeV design based on an RFQ followed by a normal-conducting (NC) DTL main linac. Both options are assumed to use a LEDA-scaled RFQ design and both options can meet the accelerator requirements for a 125-mA, 40-MeV, D-Li Fusion Neutron Facility. Option 1 is significantly more complex to fabricate and operate. Option 2 may offer several advantages including simpler operation however will be more costly to operate due to the additional electrical power required for a fully NC main linac.

Technology readiness levels (TRLs) were reviewed for the applicable accelerator technology. All proposed accelerator technologies have been successfully demonstrated in relevant operational environments that can meet some mission requirements. Only the RFQ has been recently demonstrated at the prototype level in a relevant operational environment for the proposed application. The TRL levels for the accelerator systems as applied to this application therefore range from TRL 6-7.

Several of the design studies, in addition to other reference sources, established a basis of estimate to compare Option 1 and Option 2 costs. Cost scaling factors were developed and used to estimate the accelerator system costs for each option. The results indicate that the total costs for either option are very similar: $74M for Option 1 and $70M for Option 2. These totals include only the major accelerator systems that contribute to the majority of the accelerator costs.

The estimated total accelerator project cost is approximately $100M and includes design, project management, instrumentation and controls, and other project costs but does not include institutional overheads.

2.0 INTRODUCTION

In 2018 a community workshop was held by the US fusion materials community to assess the value of a Fusion Prototypic Neutron Source (FPNS) focused on understanding materials degradation in a fusion environment [1]. The workshop concluded that a near-term, moderate cost FPNS would advance the current state of scientific understanding of materials degradation in the intense fusion neutron environment and that such a facility would be an asset to the US fusion program.

The primary goal of building a FPNS is to provide a source of neutrons at relevant energies and fluxes in a test station in the next 5-10 years, in a cost-effective manner. Several options for such a facility are being explored, including a moderate current, 40 MeV D-Li Fusion Neutron Facility much like the IFMIF-EVEDA-LIPAc [2] planned through an international collaboration in support of the ITER Project [3].

LANL has been requested to provide an assessment of appropriate accelerator technology for such a D-Li Fusion Neutron Facility. This report contains the details of this assessment. Included is an evaluation of both room-temperature (RT) and superconducting RF (SCRF) accelerator technology, including the maturity and feasibility of these technologies. Two accelerator options are presented based on the technology assessment and accelerator requirements for the facility. A cost range and basis of estimate for each option is included.

3.0 ACCELERATOR SYSTEM REQUIREMENTS

Figure 1 is a schematic layout of the major accelerator system components for a D-Li fusion neutron facility. The accelerator specifications have been captured directly from the IFMIF-EVEDA-LIPAc requirements [2] and are listed below:

- Ion Source and Injector – 140 mA D^+, DC/CW operation (pulsed capability for tuning), 100 keV, transverse output emittance <0.25 π-mm-mrad.
- Low-Energy Beam Transport (LEBT) – 2 solenoid, gas neutralization, electron trap
- RFQ – 100 keV to 5 MeV, 125 mA CW
- Medium-Energy Beam Transport (MEBT) – 4-5quadrupoles, 2 multi-gap buncher cavities
- Main Linac – 5 MeV to 40 MeV, 125 mA CW
- High-Energy Beam Transport (includes beam expander optics) – quadrupole magnet focusing lattice for beam transport, multipole magnets for beam expansion and 2D uniform distribution, final configuration TBD based on Li target geometry.

The assumed baseline is the IFMIF design. In this design, the main linac consists of four SCRF cryomodules each containing multiple, 175-MHz, multigap, half-wave resonator (HWR) cavities to accelerate the beam and SC solenoids for transverse beam focusing. The design output energies of the four SCRF cryomodules are 9 MeV, 14.5 MeV, 26 MeV, and 40 MeV, respectively.

Figure 1 – Schematic layout of a generic 40-MeV, D^+ linac for D-Li neutron production.

4.0 ANALYSIS OF ALTERNATIVES (AOA)

Several alternative accelerator designs were proposed in the recent past for a D-Li fusion neutron facility to generate 14-MeV neutrons. These proposed accelerator designs included both normal-conducting and superconducting main accelerators following a RFQ accelerator for initial acceleration of the D^+ beam. The IFMIF project has selected superconducting accelerator technology using half-wave resonators as the baseline for their main linac. However, since a major goal of this assessment is to develop a cost-effective solution that also meets the performance requirements for a moderate-energy D-Li fusion neutron facility, several past designs have been evaluated and will be used to propose options for the proposed US facility.

As the beam power increases and becomes comparable to the RF structure power required (high beam loading), the use of normal-conducting accelerator structures becomes more attractive and may lead to a lower-cost option as compared to using SCRF technology. This is particularly the case for a relatively low-energy accelerator. High-energy accelerators such as the Spallation Neutron Source (SNS) [4] or the European Spallation Source (ESS) [5] benefit from the use of SCRF. For these facilities the advantages of SCRF are realized primarily as overall power savings due to the final high beam energy (>1 GeV) and from the large apertures that reduce beam losses at high energy where these losses have the highest beam powers. However, both the SNS and ESS use NC accelerators initially up to approximately 100 MeV beam energy for efficiency of beam capture and acceleration.

The most relevant alternative designs include initial designs proposed at LANL including modification and reuse of the Low-Energy Demonstration Accelerator (LEDA), an early design agreed to by consensus of the fusion and accelerator communities (FMIF), and the presently accepted IFMIF design. Details of each of these alternatives are included in the subsections below. These alternatives are also the basis of estimate of costs for the options proposed in Section 5.0.

4.1 LANL High-Flux Accelerator-Based Neutron Source for Fusion Materials and Technology Testing (1989)

An accelerator design concept for a high-flux accelerator based neutron source for fusion materials and technology testing was presented by LANL in 1989 at the IFMIF Workshop in San Diego, CA [6]. This proposed design is based on the Fusion Materials Irradiation Test (FMIT) Facility with additional improvements. Table 1 summarizes the accelerator parameters for this design.

Accelerator technology improvements incorporated since FMIT include:

- A better analytical understanding of emittance growth, space-charge effects, and halo reduction.
- Use of ramped linac accelerating gradients to preserve longitudinal beam emittance.
- Use of permanent-magnet quadrupoles (PMQs) to provide strong low-energy focusing, preserving transverse beam emittance.
- Use of higher RF frequencies to reduce beam emittance growth (lower charge per micropulse) and to allow more compact accelerating structures.
- Use of improved beam-dynamics and high-order optics codes for simulating high-current beams and for controlling the spatial intensity of the beam, respectively.

It should be noted that these improvements have become standard practice in designing most modern high-power accelerators.

This design assumes 100-keV injection into a 3-MeV 175-MHz RFQ followed by a NC 35-MeV 350-MHz DTL. The DTL operating frequency was doubled under the assumption that beam funneling of two RFQ accelerators would be required if higher beam currents (x2) were desired. The DTL is assumed to have 4 tanks that allow energy variations in discrete steps of the final output beam energy (20, 25, 30, and 35 MeV) to the lithium target test region. The HEBT contains a beam expander based on a single octupole magnet followed by a defocusing quadrupole/focusing quadrupole magnet combination for setting the final beam size and distribution, generating a nearly uniform, rectangular beam distribution at the target. The accelerator design specifications presented are supported by beam physics or engineering design calculations.

The 1989 report highlights several accelerator technical issues:

- Beam losses in the accelerator and HEBT – activation levels need to allow for hands-on maintenance (10^{-6}/m). This is the goal of all modern accelerator designs.
- Accelerator Efficiency – RF costs dominant overall accelerator costs. Design should include cost optimization.
- Beam Energy Variability – Design uses a DTL as the main accelerating structure. This allows only discrete output beam energies by turning off DTL tanks or operating RF out of time. Small energy increments are possible by actively rotating DTL individual post couplers in a DTL tank, however this adds complexity and may increase beam losses.

Cost information was provided and the estimated cost of the full fusion materials and technology facility is $352M (2019$) based on escalating the cited costs in Ref. 6 by 3% per year. Estimated cost of the accelerator system is $85M (2019$). Details of the costing can be found in Section 6.

Table 1 – Accelerator specifications for the proposed High-Flux Accelerator-Based Neutron Source for Fusion Materials and Technology Testing.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	Not available
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	3.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.36
Structure Power (MW)	0.3
Total RF Power (MW)	0.66
Beam Loading (%)	55
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.27
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	0.46
Structure Length (m)	5.4
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz multi-gap cavities
MEBT Length (m)	Not available
Main Accelerator	
Structure Type	DTL
RF Frequency (MHz)	350
Input Energy (MeV)	3.0
Output Energy (MeV)	35.0
No. Structure Segments	4
Input Beam Current (mA)	125
Output Beam Current (mA)	125
Beam Power (MW)	4.0
Structure Power (MW)	3.3
Total RF Power (MW)	7.3
Beam Loading (%)	55
Transverse Focusing Type	Quadrupole magnets
Quadrupole Gradients (T/m)	120.0-100.0
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	0.51
Accelerating Gradient (MV/m)	3.0-4.0
Structure Length (m)	13
High-Energy Beam Transport (HEBT)	Beam Expander - Octupole, D-quad, F-quad
RF Systems	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystron

4.2 Fusion Materials Irradiation Facility (FMIF 1992)

A draft report was issued in 1992 by the FMIF Working Group [7] that established accelerator design specifications for a 14-MeV fusion materials irradiation facility capable of providing a neutron flux equivalent to a neutron wall loading of 2 MW/m^2 to a 1-liter irradiation volume. The accelerator design specifications proposed are very similar to those proposed by LANL in 1989 with a few differences.

This design assumes 100-keV injection into a 2-MeV 175-MHz RFQ followed by a hybrid NC-SCRF 40-MeV, 350-MHz DTL. The DTL operating frequency was doubled under the assumption that beam funneling of two RFQ accelerators would be required if higher beam currents (x2) were desired due to ion source limitations. The DTL design uses four tanks that allow energy variations in discrete steps of the final output beam energy (8, 30, 35, and 40 MeV) delivered to the lithium-target test region. The DTL is divided into two major sections: Section 1 is a NC 350-MHz DTL accelerating the beam to 8 MeV. Section 2 contains three 350-MHz SCRF DTL sections accelerating the beam to the final 40-MeV energy. Beam energy variability is provided by changing the operating parameters of the SCRF DTL sections. The HEBT provides magnetic focusing for beam transport to a beam dump for tuning and target safety, and also contains a beam expander for setting the final beam size and distribution at the target. Table 2 summarizes the accelerator parameters for this design.

The accelerator design specifications presented are not supported by beam physics or engineering design calculations. Additionally, no cost information was provided.

4.3 LANL LEDA (2003)

A study was done in 2003 on the potential use of the LANL Low-Energy Demonstration Accelerator (LEDA) Facility for initial testing of Fusion Materials [8]. Two options were presented, both of which used the LEDA RFQ in modified form as the first stage of D^+ beam acceleration. Superconducting accelerating cavities follow the RFQ to accelerate the beam to the final 40-MeV beam energy. Although not specified, it is assumed that the SCRF cavities proposed would be 350-MHz multi-gap spoke resonators based on the Accelerator Production of Tritium (APT) [9] cavity designs. It is assumed that these SCRF designs were also used as the basis of the costs quoted. These costs seem high in comparison to other alternatives based on the limited cost details available. Currently the LEDA RFQ is in storage at LANL minus the ion source/injector and could potentially be available for repurposing for a new 14-MeV D-Li fusion neutron facility.

Table 3 summarizes the two options investigated based on upgrading the LEDA RFQ. The first option provides a 50-mA deuterium beam, limited by the RFQ transmission at 350 MHZ, by changing the vanes in the RFQ to support efficient D^+ acceleration while still operating at the original 350-MHz RF frequency. This option would have allowed for reuse of the then-existing 350-MHz APT klystrons, however these klystrons have since been salvaged and are no longer available. The estimated cost of the accelerator upgrade is $152M (2019$).

The second option is based on the requirement to generate a 125-mA 40-MeV D^+ beam. This option requires building a new RFQ operating at 175 MHz to allow for higher beam transmission in the RFQ and a new associated 175-MHz RF system. This option, like the first, assumes the use of 350-MHz multi-gap spoke resonators following the RFQ to reach 40 MeV. Cost of this option is significantly higher due to the added cost of the new RFQ and RF system. The estimated accelerator cost is $209M (2019$) based on escalating costs 3% per year.

Table 2 – Accelerator specifications for the proposed 1992 Fusion Materials Irradiation Facility.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.075-0.125
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.2-0.8
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.075-0.125
Output Energy (MeV)	2.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.24
Structure Power (MW)	TBD
Total RF Power (MW)	TBD
Beam Loading (%)	TBD
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.4
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	Not available
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz multi-gap cavities
MEBT Length (m)	Not available
Main Accelerator	
Structure Type	DTL (RT + SCRF)
RF Frequency (MHz)	350
Input Energy (MeV)	2.0
Output Energy (MeV)	40.0
No. Structure Segments	4
Input Beam Current (mA)	125
Output Beam Current (mA)	125
Beam Power (MW)	4.75
Structure Power (MW)	Not available
Total RF Power (MW)	Not available
Beam Loading (%)	Not available
Transverse Focusing Type	Quadrupole magnets
Quadrupole Gradients (T/m)	Not available
Output Transverse Emittance (π-mm-mrad, rms, norm)	Not available
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	Not available
Accelerating Gradient (MV/m)	Not available
Structure Length (m)	Not available
High-Energy Beam Transport (HEBT)	Not available
RF Systems	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystron

Table 3 – Two proposed SCRF LEDA-based accelerator options to generate a 40-MeV D^+ beam.

	LEDA Option 1	**LEDA Option 2**
Ion Source		
Species	D+	D+
Output Beam Current (mA)	140	140
Output Energy (MeV)	0.075	0.075
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3	0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap	2-Solenoid LEBT with gas neutralization and electron trap
RFQ		
Type	4-vane	4-vane
RF Frequency (MHz)	350	175
Input Energy (MeV)	0.075	0.075
Output Energy (MeV)	6.7	6.7
Input Beam Current (mA)	140	140
Output Beam Current (mA)	50	125
Beam Power (MW)	0.33	0.825
Structure Power (MW)	Not available	Not available
Total RF Power (MW)	Not available	Not available
Beam Loading (%)	Not available	Not available
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.4	<0.4
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4	<0.4
Structure Length (m)	8.0	8.0
Medium Energy Beam Transport (MEBT)		
Quadrupole Magnets	4	4
Bunchers	2, 350-MHz multi-gap cavities	2, 350-MHz multi-gap cavities
MEBT Length (m)	TBD	TBD
Main Accelerator		
Structure Type	SCRF Multi-gap Spokes	SCRF Multi-gap Spokes
RF Frequency (MHz)	350	350
Input Energy (MeV)	6.7	6.7
Output Energy (MeV)	40.0	40.0
No. Structure Segments	Not available	Not available
Input Beam Current (mA)	125	125
Output Beam Current (mA)	125	125
Beam Power (MW)	1.67	4.16
Structure Power (MW)	Not available	Not available
Total RF Power (MW)	Not available	Not available
Beam Loading (%)	Not available	Not available
Transverse Focusing Type	Quadrupole magnets	Quadrupole magnets
Quadrupole Gradients (T/m)	Not available	Not available
Output Transverse Emittance (π-mm-mrad, rms, norm)	Not available	Not available
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	Not available	Not available
Accelerating Gradient (MV/m)	Not available	Not available
Structure Length (m)	Not available	Not available
High-Energy Beam Transport (HEBT)	Not available	Not available
RF Systems	RFQ, DTL – 350 MHz Klystrons	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystrons

Alternative LEDA Option

As part of this Alternatives Analysis an additional alternative was recently investigated that uses the LEDA RFQ in its current configuration to accelerate a deuterium beam. Beam dynamics simulations were performed using a BEAMPATH [10] model of the LEDA RFQ. The goal of the simulations was to determine the maximum D^+ beam current possible using the existing RFQ vanes. Operating the RFQ at 250 MHz rather than 350 MHz (with no RFQ structure modifications), and at an injection energy of 76.8 keV, resulted in an approximate 60% beam transmission with an output beam current of 75 mA and final beam energy of 6.7 MeV for an input beam current of 125 mA. Table 4 summarizes the BEAMPATH simulation results. If a lower CW beam current at the target cell is acceptable, or higher losses and activation tolerated in the RFQ (higher injected D^+ beam current needed to reach 125 mA), reuse of the LEDA RFQ may be a viable option and could lead to substantial cost savings (~$11M). Availability of high-power RF sources at 250 MHz will need to be explored but may be within the current specifications of other near-frequency RF sources such as the Diacrode. In addition, a main linac design to 40 MeV using either NC or SCRF technology and operating at 250-MHz will need to be designed.

Table 4 – BEAMPATH simulation results and parameters for operating the LEDA RFQ at 250 MHz to accelerate deuterons to 6.7 MeV.

Parameter	**LEDA RFQ (250 MHz)**
Frequency (MHz)	250
Injection Energy (keV)	76.8
Final Energy (MeV)	6.7
Number of Cells	430
Length (m)	7.93
Intervane Voltage (kV)	66….116
Synchronous Phase (deg)	-33
Aperture (cm)	0.24
Modulation Factor (Accelerator Section)	2.12
Minimum Normalized Transverse Acceptance (π cm mrad)	0.22
Maximum Normalized Longitudinal Acceptance (π cm mrad)	2.8
Transverse Current Limit (mA)	200
Longitudinal Current Limit (mA)	180
Emax/ Ekilpatrick	1.9 (x 1.07)
RF Power (Cavity+Beam, kWt)	680 + 400 = 1080
Beam Current Input (mA)	125
Input RMS Normalized Emittance (π cm mrad)	0.03
Emittance Growth	0.75
Single Accelerated Bunch Transmission	58%
Total Transmission (transverse loss only)	62%
Beam Current Output (mA)	75
2-RMS Relative Energy Spread dW/W	0.018

4.4 IFMIF-EVEDA-LIPAc (2017)

The present IFMIF-EVEDA-LIPAc linac design [2, 11] is considered the reference design against which all other alternatives will be compared for both performance and cost. This design has undergone considerable evolution, taking advantage of most advances in understanding beam losses and mechanisms of beam halo generation in high-current high-power accelerators [12]. Additionally, the design has evolved from first considering a conventional Alvarez DTL as the main linac to considering the use of both NC and SCRF interdigital structures, and finally converging on the present main linac design which uses SCRF half-wave resonators (HWRs) [13]. Use of a SCRF linac substantially reduces the required RF power and the future facility operating cost. Figure 2 shows a schematic layout of the IFMIF-EVEDA-LIPAc linac design. Table 5 summarizes the accelerator parameters for a single-linac system.

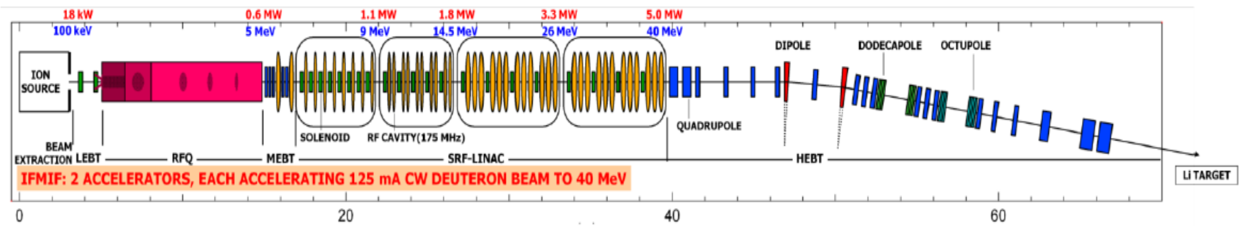

Figure 2 – Schematic layout of the proposed IFMIF-EVEDA-LIPAc linac design [12].

Estimated cost of the 40-MeV IFMIF-EVEDA-LIPAc linac system is unknown due to the unavailability of cost information. As of 2007, $219.9M (2019$) was budgeted for the project including the 9-MeV LIPAc demonstration using available IFMIF cost conversions and assuming in-kind contributions from the international collaboration [14].

4.5 Summary of Design Alternatives

Table 6 provides a brief summary and comparison of the design alternatives reviewed. The differences highlighted are the differences in accelerator technology used for each design, the specific energy transitions between accelerator types, the total power required for each system and the estimated cost. Each of these systems meet the requirements for a 14-MeV D-Li Fusion Neutron irradiation facility.

5.0 ACCELERATOR OPTIONS

Based on the analysis of alternatives, several viable accelerator options exist. Two options are presented below. Option 1 directly reproduces the present SCRF based IFMIF design based on costs to design and fabricate the accelerator in the US with some potential foreign vendor participation. Option 2 replaces the SCRF linac with a NC DTL as an alternative option that may have some operational advantages. Other combinations are certainly possible based on cost and complexity. Both options assume there will be no access to IFMIF design information, requiring the design of all accelerator components to be completed by ORNL, another partner laboratory, or a commercial accelerator vendor. A potential RFQ design is based on the successful design principles used to design the LANL LEDA RFQ. This design has not been optimized but is included as an example in the options presented. All RFQ design parameters and simulation results are based on extending the LEDA RFQ design to 175 MHZ (from 350 MHz) to efficiently accelerate a 125-mA D^+ beam. All quoted costs were derived using the basis of estimate information in Section 6.

Table 5 – Accelerator specifications for the present IFMIF-EVEDA-LIPAc linac design.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	5.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.61
Structure Power (MW)	0.56
Total RF Power (MW)	1.18
Beam Loading (%)	52
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.31
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	9.6
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	5
Bunchers	2, 5-gap IH cavities
MEBT Length (m)	2
Main Accelerator	
Structure Type	SC 2-gap HWR
RF Frequency (MHz)	175
Input Energy (MeV)	5.0
Output Energy (MeV)	40.0
No. Structure Segments	4 Cryomodules
Cavity Design β	β=0.094, β=0.094, β=0.164, β=0.164
No. Cavities per Cryomodule	Cryomodules 1,2 = 6 Cryomodules 3,4 = 4
Cryomodule output energy (MeV)	9.0, 14.5, 26.0, 40.0
Input Beam Current (mA)	125
Output Beam Current (mA)	125
Beam Power (MW)	4.4
Structure Power (MW)	0.18
Total RF Power (MW)	5.58
Beam Loading (%)	79
Transverse Focusing Type	SC EM Solenoids
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	Not available
Accelerating Gradient (MV/m)	4.5
Structure Length (m)	22.7
High-Energy Beam Transport (HEBT)	Not available
RF Systems	48 220 kW, 175 MHz Tetrodes

Table 6 – Summary of reviewed design alternatives.

	High-Flux Source (1989)	FMIF (1992)	LEDA (2003)	IFMIF-EVEDA-LIPAc (2017)
Ion Source				
Species	D+	D+	D+	D+
Output Beam Current (mA)	140	140	140	140
Output Energy (MeV)	0.100	0.075-0.125	0.075	0.100
RFQ				
Type	4-vane	4-vane	4-vane	4-vane
RF Frequency (MHz)	175	175	350 or 175	175
Input Energy (MeV)	0.100	0.075-0.125	0.075	0.100
Output Energy (MeV)	3.0	2.0	6.7	5.0
Input Beam Current (mA)	140	140	140	140
Output Beam Current (mA)	125	125	50-125	125
Beam Power (MW)	0.36	0.24	0.33-0.825	0.61
Structure Power (MW)	0.30	0.2 (estimated)	Not available	0.56
Total RF Power (MW)	0.66	0.44	-	1.17
Beam Loading (%)	55	55	-	52
Structure Length (m)	5.4	Not available	8.0	9.6
Main Accelerator				
Structure Type	DTL	DTL	DTL or SCRF	SC 2-gap HWR
RF Frequency (MHz)	350	350	175 or 350	175
Input Energy (MeV)	3.0	2.0	6.7	5.0
Output Energy (MeV)	35.0	40.0	40.0	40.0
Output Beam Current (mA)	125	125	125	125
Beam Power (MW)	4.0	4.75	1.67-4.16	4.4
Structure Power (MW)	3.3	3.92 (estimated*)	Not available	0.18
Total RF Power (MW)	7.3	8.7	-	5.58
Beam Loading (%)	55	Not available	Not available	79
Accelerating Gradient (MV/m)	3.0-4.0	Not available	Not available	4.5
Structure Length (m)	13.0	Not available	Not available	22.7
Total RF Power (MW)	7.96	9.14 (estimated*)	-	5.75
RF Systems	175 MHz Tetrodes	RFQ – 175 MHz Tetrode, DTL – 350 MHz Klystron	175 MHz Tetrode, 350 MHz Klystron	48 - 220 kW, 175 MHz Tetrodes
Cost (2019$)	$85M	Not available	$152M-$209M	Not available

*Estimated by scaling 1989 results by energy.

5.1 Option 1: Radiofrequency Quadrupole (RFQ) + Superconducting RF (SCRF) Linac

Option 1 essentially reproduces the IFMIF-EVEDA-LIPAc linac design using a LEDA-based RFQ and a similar SCRF linac using HWR cavities. Figure 3 shows a schematic layout of this option. Table 7 summarizes the general RFQ and SCRF linac parameters. The RFQ output energy is 5-MeV, but cost tradeoffs based on alternative RFQ lengths and final output energies could be considered to optimize the overall linac costs. Also shown are preliminary RFQ simulation results (see Table 8 and Fig. 4) used to estimate the total RF structure power required. Table 9 summarizes the estimated average cost by subsystem for the largest system cost components: the RFQ, the SCRF linac, the RF system, and the cryoplant based on the cost scaling factors developed in Section 6 below. Estimated costs do not include institutional overheads.

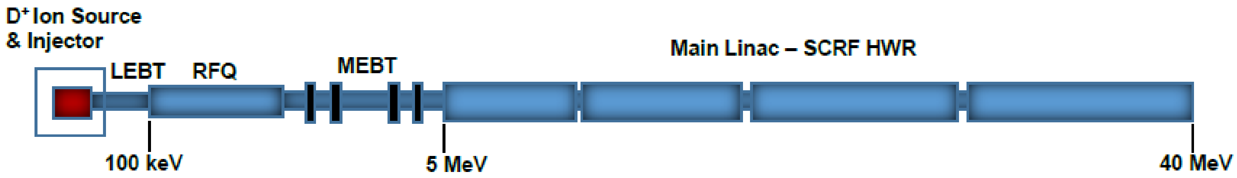

Figure 3 – Option 1 schematic layout.

Table 7 – Option 1 accelerator specifications.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ (LEDA Based)	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	5.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.61
Structure Power (MW)	0.56
Total RF Power (MW)	1.17
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	9.6
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	5
Bunchers	2, 5-gap IH cavities
MEBT Length (m)	2
Main Accelerator	
Structure Type	SC 2-gap HWR
RF Frequency (MHz)	175
Output Energy (MeV)	40.0
No. Structure Segments	4 Cryomodules
Cavity Design β	β=0.094, β=0.094, β=0.164, β=0.164
No. Cavities per Cryomodule	Cryomodules 1,2 = 6 Cryomodules 3,4 = 4
Cryomodule output energy (MeV)	9.0, 14.5, 26.0, 40.0
Output Beam Current (mA)	125
Beam Power (MW)	4.4
Structure Power (MW)	0.2
Total RF Power (MW)	4.6
Transverse Focusing Type	SC EM Solenoids
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3
Structure Length (m)	22.7
Total RF Power – RFQ + SCRF Linac (MW)	5.8

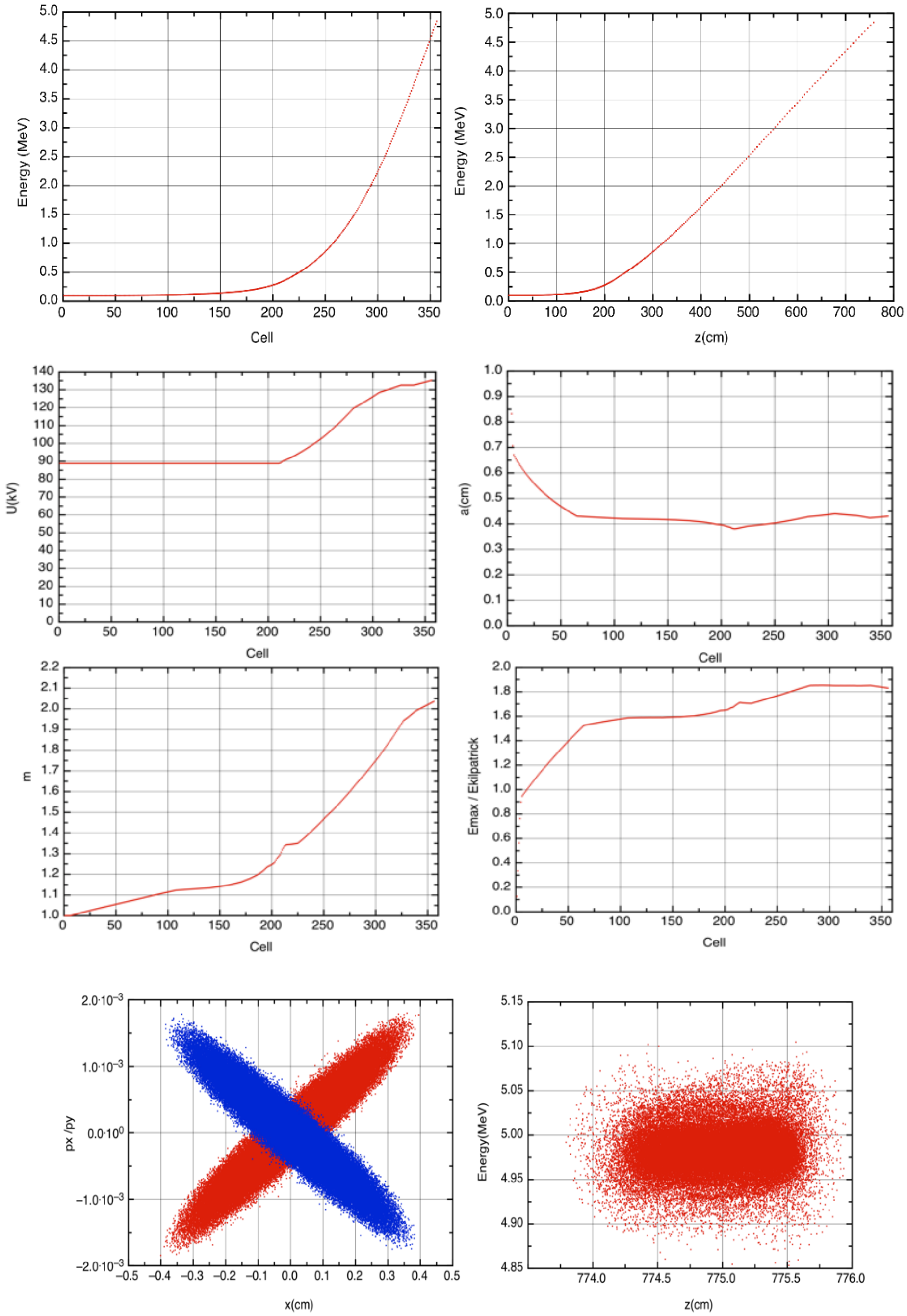

Figure 4 – Beam simulation results for a 175-MHz LEDA-scaled D^+ RFQ.

Table 8 – Simulation results for a 175-MHz LEDA-scaled D^+ RFQ.

Parameter	Value
Frequency (MHz)	175
Injection Energy (keV)	100
Final Energy (MeV)	5
Number of Cells	360
Length (m)	7.83
Intervane Voltage (kV)	88….136
Synchronous Phase (deg)	-35
Aperture (cm)	0.4
Max Modulation Factor	2.12
End-of-Buncher Norm Transv Acceptance (π cm mrad)	0.4
End-of-Buncher Norm Long Acceptance (π cm mrad)	1.0
Transverse Current Limit (A)	0.3
Longitudinal Current Limit (A)	0.3
Emax/ Ekilpatrick	1.85 (x 1.07)
RF Power (Cavity + Beam, kWt)	564+550 = 1114
Beam Current Input (mA)	125
Input RMS Norm Emittance (π cm mrad)	0.03
Emittance Growth Factor	1.0
Single Accelerated Bunch Transmission (%)	88.6
Total Transmission (transverse loss only; %)	90.0
2-RMS Relative Energy Spread dW/W	8.84×10^{-3}

Table 9 – Option 1 Cost Summary by Subsystem

Subsystem	2019 Cost ($M)	Basis of Estimate
RFQ (175 MHz)	11.28	Low cost/m from 1989 IFMIF; High cost/m from IFMIF-EVEDA project
SCRF HWR (175 MHz)	34.05	SARAF cost/m
RF Power	19.94	Low cost/MW from SARAF Project; High cost/MW from 1989 High Flux Source
Cryoplant	8.50	MSU/FRIB
Total	73.76	

5.2 Option 2: Radiofrequency Quadrupole (RFQ) + Normal-Conducting (NC) Linac

Option 2 consists of a 175-MHz, 5-MeV, LEDA-based RFQ followed by a 175-MHz, NC Alvarez-type DTL to 40 MeV. Table 10 summarizes the general RFQ and DTL linac parameters for this option. A schematic layout is shown in Fig. 5. Just as for Option 1, cost tradeoffs based on alternative RFQ lengths and final output energies could be considered to optimize the overall linac costs.

Table 10 – Option 2 accelerator specifications.

Ion Source	
Species	D+
Output Beam Current (mA)	140
Output Energy (MeV)	0.100
Output Transverse Emittance (π-mm-mrad, rms, norm)	<0.3
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ (LEDA Based)	
Type	4-vane
RF Frequency (MHz)	175
Input Energy (MeV)	0.100
Output Energy (MeV)	5.0
Input Beam Current (mA)	140
Output Beam Current (mA)	125
Beam Power (MW)	0.61
Structure Power (MW)	0.56
Total RF Power (MW)	1.17
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.30
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	9.6
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	4
Bunchers	2, 175-MHz, 2-gap cavities
MEBT Length (m)	2
Main Accelerator	
Structure Type	NC DTL
RF Frequency (MHz)	175
Output Energy (MeV)	40.0
No. Structure Segments	TBD
Output Beam Current (mA)	125
Beam Power (MW)	4.4
Structure Power (MW)	2.0
Total RF Power (MW)	6.4
Transverse Focusing Type	Permanent-Magnet Quadrupoles
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.3
Structure Length (m)	23
Total RF Power – RFQ + SCRF Linac (MW)	7.6

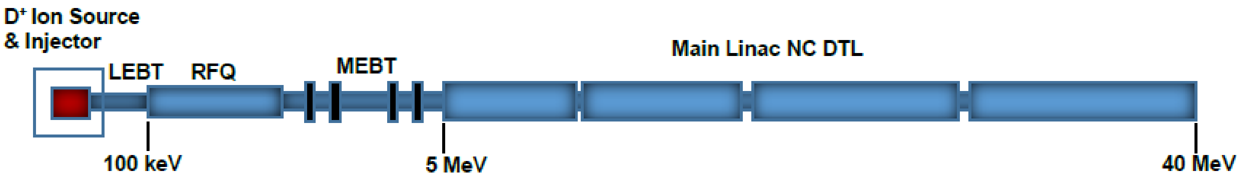

Figure 5 – Option 2 schematic layout.

Preliminary design simulation results estimate the DTL structure power required, the total length of the DTL structure, and the beam dynamics performance (emittance growth, transmission, etc.). These results are summarized in Table 11 below. The proposed DTL accelerating gradient is 1.75 MV/m and the nominal operating synchronous phase of the beam is -30 deg. This results in an overall DTL structure length of 23 m and a total structure power of approximately 2 MW. Figure 6 shows the preliminary structure calculation results including the DTL cell and drift-tube geometries assumed. A lower accelerating gradient was selected to maintain a reasonable total structure power as a trade-off with overall DTL length. It is assumed that accelerator tunnel length costs are significantly lower per meter than are high-power RF costs per MW. However, these parameters and associated costs can be optimized during a more detailed design study. Figure 7 summarizes additional DTL design simulation results.

Table 12 summarizes the estimated average cost by subsystem for the largest system cost components: the RFQ, the NC DTL, and the RF system based on the cost scaling factors developed in Section 6 below. Estimated costs do not include institutional overheads.

Table 11 – Simulation results for a 175-MHz D^+ NC DTL.

Parameter	Value
Frequency (MHz)	175
Injection Energy (MeV)	5
Final Energy (MeV)	40
Structure Type	Alvarez (0-mode)
Focusing Period	$2\beta\lambda$
Number of Accelerating Gaps	98
Length (m)	23.36
Accelerating Gradient (MV/m)	1.75
Transit Time Factor	0.9-0.95
Synchronous Phase (deg)	-30
Aperture (cm)	1.0
Quadrupole Accelerating Gradient (T/cm)	0.8-0.75
Norm Transv Acceptance (π cm mrad)	3.35
Norm Long Acceptance (π cm mrad)	2.29
RF Power (Cavity + Beam, MW)	2.0+3.9 = 5.9
Beam Current Input (mA)	125
Input RMS Norm Emittance (π cm mrad)	0.03
Emittance Growth Factor	1.14
Single Accelerated Bunch Transmission (%)	99.97
Total Transmission (transverse loss only; %)	99.97
2-RMS Relative Energy Spread dW/W	3.3×10^{-3}

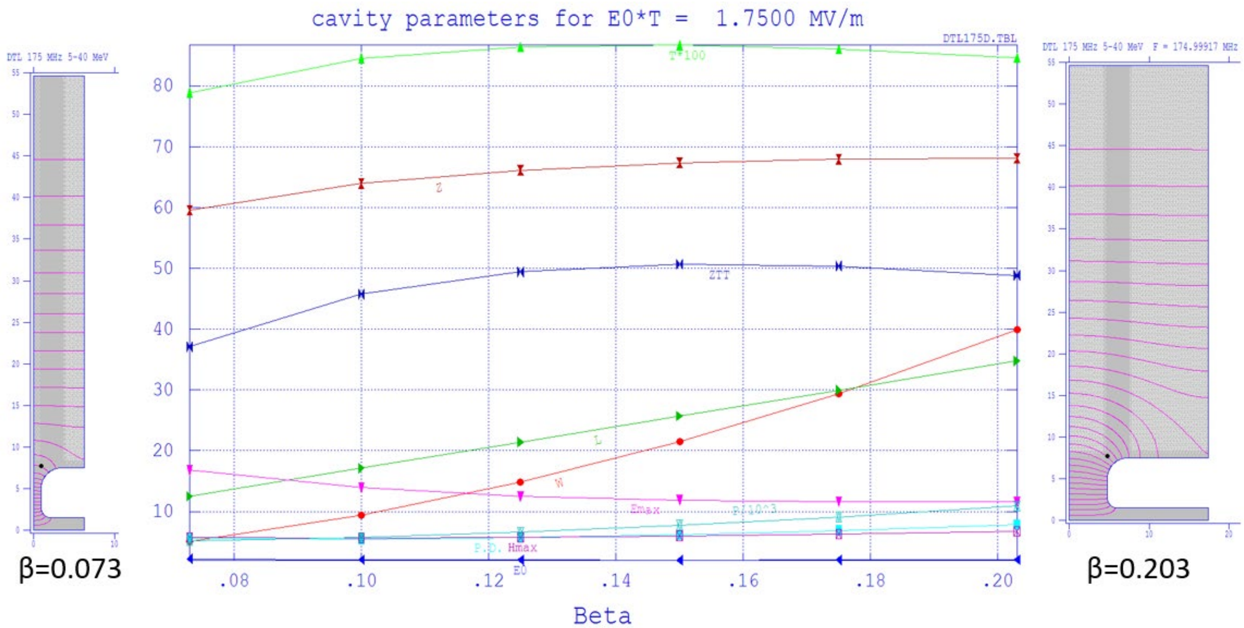

Figure 6 – Preliminary structure simulation results for Option 2.

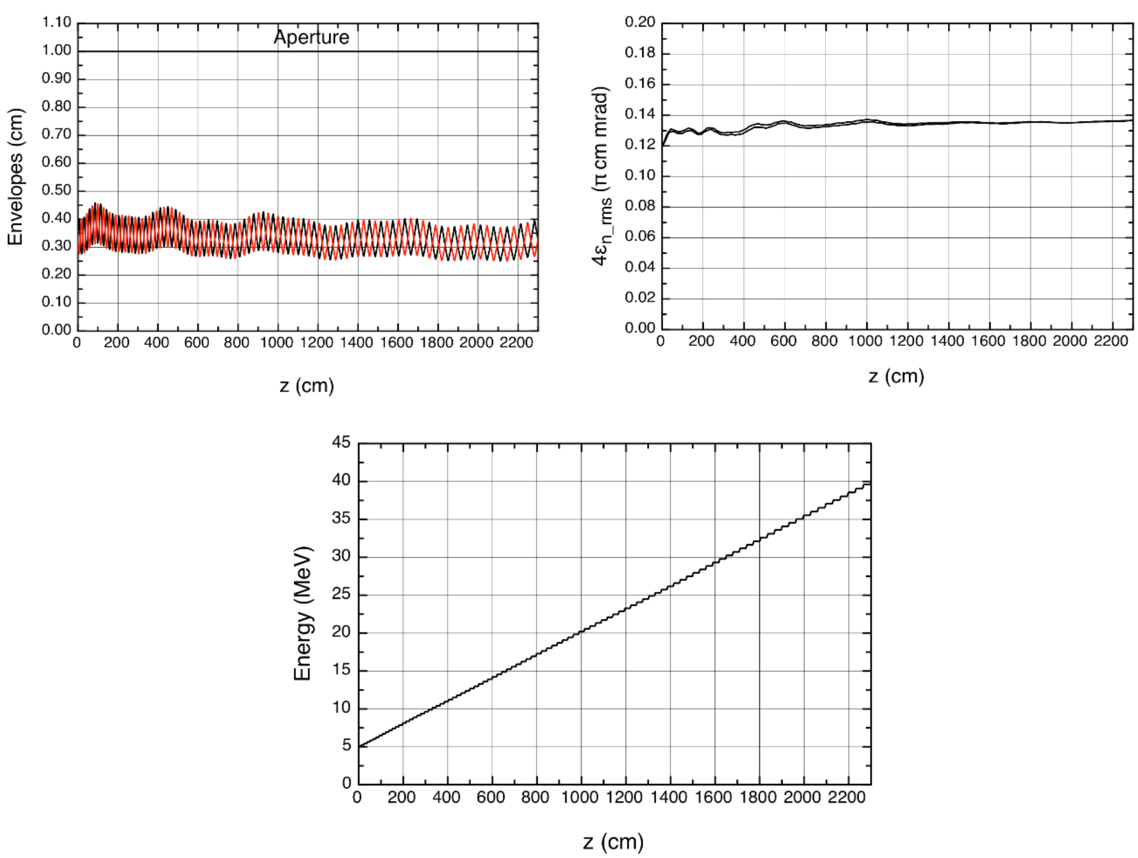

Figure 7 – Beam simulation results for a 175-MHz NC D^+ DTL.

Table 12 – Option-2 Cost Summary by Subsystem

Subsystem	2019 Cost ($M)	Basis of Estimate
RFQ (175 MHz)	11.28	Low cost/m from 1989 IFMIF; High cost/m from IFMIF-EVEDA project
DTL (175 MHz)	32.82	Low cost/m from 1989 High Flux Source; high cost/m from 1996 IFMIF design pre-SCRF assuming DTL
RF Power	26.15	Low cost/MW from SARAF Project; High cost/MW from 1989 High Flux Source
Total	70.25	

6.0 COST ESTIMATE – BASIS OF ESTIMATE

A cost estimate for each accelerator option in Section 5 was developed using information from three primary sources [6, 15, 16]. Cost information from these sources was appropriately escalated using a 3%/year escalation rate to determine 2019 estimated costs. Individual estimates were developed for the six major accelerator subsystems contributing to the majority of the integrated accelerator cost for a 40-MeV fusion neutron facility based on the overall accelerator layout: 1) the RFQ, 2) a SCRF linac, 3) a NC DTL, 4) the HEBT, 5) the RF system, and 6) the cryoplant. This allows the flexibility to estimate additional combinations of subsystem technology if desired. In the case where several bases of estimate are available for a subsystem, cost scaling factors are used that reflect the average cost per unit for each subsystem.

6.1 IFMIF Accelerator Equipment Cost Summary (1996)

A site-independent online accelerator system cost summary developed in December 1996 is available at http://www.frascati.enea.it/cda/CostReport/ [15]. This cost estimate integrates the in-kind contributions due to the international partnership of the IFMIF collaboration as defined at the time of the report. In 1996, the IFMIF design was based on using a NC DTL as the main linac. Costs have been normalized using a unique cost unit called the "IFMIF Conversion Factor (ICF)" where 1 ICF = $1.00 US (1996). Table 7 summarizes the accelerator equipment costs for a single 125-mA, D^+, NC linac (RFQ+ DTL) using this methodology.

The overall costs in Ref 15 are subdivided into "Off Site" costs that include all accelerator equipment costs minus "On Site" installation and commissioning. The accelerator equipment costs are further subdivided by first and second accelerator system. The accelerator equipment costs associated with building the first unit are higher, compared to the second system that takes advantage of recurring engineering. The higher cost data was used to estimate the cost scaling factors shown in Table 13 after being appropriately escalated by 3%/year from 1996 to 2019.

Table 13 – 1996 IFMIF Accelerator Equipment Cost Summary by Subsystem

Subsystem	1992 Cost	2019 Cost
RFQ (175 MHz)	$11.6M	$22.9M
DTL (175 MHz)	$22.4M	$44.2M
HEBT	$13.4M	$26.5M
RF Power	$63.5M	$125.3M

Based on the escalated costs of Table 8, the following scale factors have been derived in $M 2019:

- 175-MHz RFQ structure cost/meter = $2.39M/meter
- 175-MHz DTL structure cost/meter = $1.45M/meter

These are calculated assuming a 5-MeV RFQ and 5-40 MeV DTL using the nominal structure lengths proposed in Ref. 13.

6.2 High Flux Source Cost Summary (1989)

Reference 6 provides a detailed breakdown by subsystem for the alternative presented in Section 4.1. Table 14 summarizes the 1989 costs for a 125-mA system. Costs escalated to 2019$ are also shown. Table 15 captures the cost subtotals by subsystem used to estimate the cost scaling factors given below. For the purpose of this estimate, the DTL cost per meter is assumed to be independent of RF frequency.

Table 14 – 1989 High-Flux Source Cost Estimate

Accelerator System Costs	($M 1989)	($M 2019)
Injector	0.80	1.94
RFQ (175 MHz)		
Structure (tank, vanes, vaccum, cooling, stand)	1.10	2.67
RF Power (tubes, DCPS, windows, coax)	0.70	1.70
Main Accelerator (350-MHz DTL)		
Structure (includes magnets and vacuum)	7.30	17.72
RF Power (tubes, DCPS, windows, coax)	11.00	26.70
High-Energy Beam Transport (HEBT)		
Magnets (quadrupoles, dipoles, vacuum)	3.70	8.98
Non-linear optics	0.60	1.46
Energy-dispersion cavity	1.60	3.88
Tune-up Beam Stop	0.40	0.97
Beam Splitter	1.70	4.13
Beam Diagnostics		
Injector (ion source + RFQ)	0.20	0.49
Main Accelerator	0.40	0.97
HEBT	1.00	2.43
Control System (15% of accelerator equipment)	4.58	11.12
Total =	35.08	85.15

Table 15 – 1989 IFMIF Accelerator Equipment Cost Summary by Subsystem

Subsystem	1989 Cost	2019 Cost
RFQ (175 MHz)	$1.1M	$2.7M
DTL (350 MHz)	$7.3M	$17.7M
HEBT	$8.0M	$19.4M
RF Power	$11.7M	$28.4M

Based on the escalated costs of Table 8, the following scale factors have been derived in $M 2019:

- 175-MHz RFQ structure cost/meter = $0.49M/meter
- 350-MHz DTL structure cost/meter = $1.36M/meter
- RFQ Power Cost /MW = $3.57M/MW

6.3 Soreq Applied Research Accelerator Facility (SARAF) Conceptual Design Cost & Schedule Report (2012)

This report provides detailed conceptual design and cost information for a CW linear accelerator capable of delivering 200 kW beams of 40-MeV, 5-mA protons and deuterons [16]. The conceptual design is based on a NC RFQ and SCRF half-wave resonators operating at a RF frequency of 176 MHz. The SARF accelerator design therefore very closely resembles the IFMIF SCRF design and is an excellent basis of estimate for the SCRF accelerator option for a D-Li Fusion Neutron Facility in particular since detailed cost information for the current IFMIF-EVEDA-LIPAc design is not available. Table 16 summarizes the SARAF accelerator parameters.

Table 17 summarizes the total SARAF project costs. Appropriate costing scale factors can be derived from the detailed costing information provided. The costing scaling factors are summarized in Table 18. These scaling factors were used to derive the cost options presented above in Section 5.

7.0 TECHNICAL READINESS LEVELS

Below is a summary of the standard Technical Readiness Levels (TRLs):

- **TRL 1 -** When a technology is at TRL 1, scientific research is beginning and those results are being used to plan future research and development. Basic principles are observed and reported.
- **TRL 2 -** TRL 2 occurs once the basic principles have been studied and those results can be applied to practical applications. TRL 2 technology is very speculative, with little to no experimental proof of concept for the technology. The technology concept and/or application have been formulated.
- **TRL 3 -** When active research and design begin, a technology is elevated to TRL 3. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. A proof-of-concept model is developed.
- **TRL 4 –** Component or breadboard validation in the laboratory environment.
- **TRL 5 -** TRL 5 is a continuation of TRL 4. Component or breadboard validation in a relevant environment.
- **TRL 6 –** System/subsystem model or prototype demonstration in a relevant environment.
- **TRL 7 -** Working model or prototype demonstrated in a relevant operational environment.
- **TRL 8 –** Actual system completed and qualified through test and demonstration.
- **TRL 9 –** Actual system proven through successful mission operations.

Table 16 – Summary of the SARAF Linac Parameters (2012).

Ion Source	
Species	D+
Output Beam Current (mA)	10
Output Energy (MeV)	0.040
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.25
Low-Energy Beam Transport (LEBT)	2-Solenoid LEBT with gas neutralization and electron trap
RFQ	
Type	4-vane
RF Frequency (MHz)	176
Input Energy (MeV)	0.040
Output Energy (MeV)	3.0
Input Beam Current (mA)	5.0
Output Beam Current (mA)	5.0
Beam Power (MW)	0.0128
Structure Power (MW)	0.126
Total RF Power (MW)	0.1328
Beam Loading (%)	9.64
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.31
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	<0.4
Structure Length (m)	3.81
Medium Energy Beam Transport (MEBT)	
Quadrupole Magnets	6
Bunchers	2, 4-gap NC Fork
MEBT Length (m)	2.04
Main Accelerator	
Structure Type	SC 2-gap HWR
RF Frequency (MHz)	176
Input Energy (MeV)	2.6
Output Energy (MeV)	40.0
No. Structure Segments	4 Cryomodules
Cavity Design β	β=0.09, β=0.16, β=0.16, β=0.16
No. Cavities per Cryomodule	β=0.09 Cryomodule 1 = 7 β=0.16 Cryomodules 2,3,4 = 7
Cryomodule output energy (MeV)	9.0, 14.5, 26.0, 40.0
Input Beam Current (mA)	5.0
Output Beam Current (mA)	5.0
Beam Power (MW)	0.187
Structure Power (MW)	0.041+0.309 = 0.350
Total RF Power (MW)	0.537
Beam Loading (%)	69.5%
Transverse Focusing Type	SC EM Solenoids
Output Transverse Emittance (π-mm-mrad, rms, norm)	0.32
Output Longitudinal Emittance (π-mm-mrad, rms, norm)	Not available
Accelerating Gradient (MV/m)	6.6, 7.3
Structure Length (m)	19.47
High-Energy Beam Transport (HEBT)	Not available
RF Systems	Not available – Assume Solid-State RF
Cryoplant	1000 kW, 4.5K

Table 17 – Summary of the SARAF Project costs (2012) Costs have been escalated by 3%/year to arrive at 2019 costs.

		FY2013 COSTS			FY2019 Costs
	LABOR	**LABOR**	**OTHER**	**TOTAL**	**COST**
ITEM	**FTE-years**	**K$**	**K$**	**K$**	**K$**
MANAGEMENT	12.2	$3,832	$537	$4,461	$5,326.88
DESIGN	9.1	$1,896	$404	$2,369	$2,828.82
RFQ	5.1	$1,062	$2,394	$4,004	$4,781.18
MEBT	2.8	$572	$736	$1,434	$1,712.34
SC CAVITIES	17.4	$3,793	$9,518	$14,945	$17,845.82
LOW-β CRYOMODULE	5.2	$1,064	$1,101	$2,354	$2,810.91
HIGH-β CRYOMODULES	11.3	$2,278	$3,251	$6,087	$7,268.49
RF SYSTEMS	5.4	$1,380	$426	$1,879	$2,243.71
SUBSYSTEMS	1.2	$256	$3,241	$4,053	$4,839.69
DIAGNOSTICS	2.1	$418	$1,311	$1,954	$2,333.27
SPARES	0.1	$16	$163	$207	$247.18
COMMISSIONING	3.1	$781	$545	$1,419	$1,694.43
AS-BUILTS & DOCUMENTATION	3.4	$716	$13	$728	$869.30
INITIAL TOOLING	5.9	$1,162	$532	$1,786	$2,132.66
CRYOPLANT	-	-	-	-	$8,0000 (estimated*)
TOTALS	**84.0**	**$19,225**	**$24,374**	**$47,680**	**$64,935**

*[17]

Table 18 – Cost-scaling factors derived from the escalated SARAF Project cost details.

Subsystem	**Cost Scaling Factor**	**Value (2019$)**
Project Management	Total Project Management Cost	10% of total project cost
Design	Total Project Design Cost	5% of total project cost
RFQ (includes LEBT)	RFQ Cost/m	$1,255K/m
MEBT	MEBT Cost/m	$840K/m
SC Cavities	SC Cavity Cost/m	$1,500K/m
RF	RF Power Cost/MW	$3,350K/MW
Instrumentation & Controls (IC)	Total IC Cost	10%-15% of accelerator equipment cost
Commissioning	Total Project Commissioning Cost	3% of total project cost
As-Built Drawings & Documentation	Total Drawing & Documentation Costs	1.5% of total project cost
Tooling	Total Project Tooling Cost	4% of total project cost

7.1 RFQ

TRL = 7

RFQ accelerators have been under continuous development and improvement for many decades for a variety of accelerator mission requirements. The RFQ accelerator is the first stage of RF acceleration in every major ion accelerator facility worldwide for a broad range of applications (CERN, LANSCE, Fermilab, Brookhaven, ORNL/SNS, ISIS/Rutherford, etc.). This is due to the ability of the RFQ to quickly bunch a low-velocity ion beam from the injector for capture and further acceleration, their high RF efficiency, their compactness, and the ability to tune the output parameters using well-defined design principles and well-benchmarked design and simulation codes.

There are essentially two RFQ accelerator configurations – 4-vane or 4-rod. The 4-vane RFQ is generally used for light-ion acceleration. This type of RFQ typically operates in the 200 MHz-400 MHz RF frequency range, with recent designs demonstrated as high as approximately 700 MHz at CERN for medical applications. The 4-rod RFQ has historically been used to accelerate heavy ions which typically requires lower RF frequencies (<200 MHz). The 4-vane RFQ is favored for high-duty-factor applications where the ability to cool the structure is very important.

Multiple operating examples of RFQs exist. Therefore, the overall TRL level for RFQs is TRL 9.

Examples that support the TRL level as applied to a D-LI Fusion Neutron Facility include the demonstrated 100-mA CW operation with protons of the LEDA [18]. In addition, the SARAF RFQ has been operational since 2014 [19], albeit at lower average beam current but CW, and most recently, the IFMIF RFQ has successfully accelerated a 125-mA deuteron beam to 5 MeV in LIPAc on July 24, 2019 [20]. All three of these RFQs have been qualified through testing and demonstration at the prototype level in a relevant operational environment. Therefore, the TRL level for the RFQ as applied to a high-current D-Li Fusion Neutron Facility is TRL 7.

7.2 NC DTL

TRL = 6

There are many examples of operating drift-tube linacs, therefore the overall TRL level for DTL structures as a proven technology is TRL 9. However, none are operating CW and accelerating high-current deuteron beams. Therefore, the TRL level for the DTL is TRL 6. Design and demonstration of a DTL meeting the performance requirements for a D-Li Fusion Neutron Facility would be required to increase the TRL level.

Several viable DTL designs have been developed over the past several decades that can meet the D-Li Fusion Neutron Facility requirements [20, 21], including a design developed for the IFMIF-EVEDA trade studies [13]. There are also more recent examples of CW DTL designs under development [22, 23, 24]. Based on the current understanding of high-current beam dynamics and the physics modeling capabilities available, it should be possible to develop a design that can perform equivalently to a SCRF linac design while meeting the performance requirements for a D-Li Fusion Neutron Facility, including low beam losses and hands-on maintainability.

7.3 SCRF LInac

TRL = 7

The first phase of the SARAF Accelerator Facility construction was completed in 2014 [25]. This phase of the project included installation of the ion source, the RFQ, and a prototype superconducting accelerating module with six HWR cavities. This initial phase of the accelerator produces a 4-MeV, CW proton beam and a high-current deuteron beam up to 5.6 MeV. The second phase of the project, scheduled for completion in 2023, includes installing the final five SCRF HWR cryomodules to reach the final 40-MeV deuteron beam energy.

The SARAF design most closely resembles a SCRF based D-Li Fusion Neutron Facility design, albeit operating at a much lower average CW beam current (5-10 mA vs. 125 mA). Demonstrating operation of an SCRF-based main linac at the higher required beam current for a D-Li Fusion Neutron Facility may be a considerable technical challenge to reach the TRL-8 level. Successful next-phase testing in the IFMIF-EVEDA-LIPAc facility would also demonstrate these performance levels and increase the overall SCRF linac TRL level.

8.0 SUMMARY & RECOMMENDATIONS

Several past design studies were reviewed and an analysis of alternatives completed to assess the range of accelerator parameters and accelerating structure types that can potentially meet the requirements of a 125-mA, 40-MeV, D-Li Fusion Neutron Facility. The design studies reviewed included past LANL designs for IFMIF and designs based on the use of modified versions of the LEDA. Also reviewed were the past IFMIF-EVEDA design iterations that explored several options for the main linac including the use of an Alvarez DTL, interdigital accelerating structures, and a SCRF HWR based main linac. Several parameter variations such as RFQ injection and final output energies, and types of main linac (NC or SCRF) proposed were noted. A more detailed study would be required to make comments on the relative parameter optimization of each reviewed design. This was not within the scope of this study.

A common set of accelerator parameters was established, based primarily on the IFMIF-EVEDA-LIPAc design:

- Ion Source and Injector – 140 mA D^+, DC/CW operation (pulsed capability for tuning), 100 keV, transverse output emittance <0.25 π-mm-mrad.
- Low-Energy Beam Transport (LEBT) – 2 solenoid, gas neutralization, electron trap
- RFQ – 100 keV to 5 MeV, 125 mA CW
- Medium-Energy Beam Transport (MEBT) – 4-5quadrupoles, 2 multi-gap buncher cavities
- Main Linac – 5 MeV to 40 MeV, 125 mA CW
- High-Energy Beam Transport (includes beam expander optics) – quadrupole magnet focusing lattice for beam transport, multipole magnets for beam expansion and 2D uniform distribution, final configuration TBD based on Li target geometry.

These parameters were used to develop two accelerator options for a green-field D-Li Fusion Neutron Facility. Option 1, as described in detail in Section 5, essentially reproduces the IFMIF-EVEDA-LIPAc design based on an RFQ and a SCRF HWR-based main linac. It is assumed that no access to detailed IFMIF design information is available and that all accelerator components will need to be redesigned. The proposed RFQ design is based on the LANL LEDA RFQ design scaled to the required 175-MHz RF frequency however other design approaches could be used. Option 2, also described in detail in Section 5, is an alternative design based on the same LEDA-scaled RFQ design and a NC DTL main linac.

Several reference sources were used as the basis of estimate and to develop cost-scaling factors. These cost-scaling factors were then applied to estimate the major system costs for each proposed accelerator option and to make an overall option cost comparison. Although there is a cost range for each subsystem, the average cost was used. Section 6 summarizes the basis-of-estimate reference sources and the cost details.

Cost Comparison Summary

The table below summarizes the cost differences by major subsystem for the two proposed accelerator options. The listed subsystems are those that contribute most to the overall accelerator costs. As can be seen, at the level of accuracy of the estimates, the two option costs are essentially the same and both fall within the expected $50M-$120M cost range. Option 2 uses approximately 2MW additional RF power at significant additional cost compared to Option 1, however, this balances out with the significant cost of the required 4K cryoplant for the SCRF main linac in Option1. The estimated operating cost of Option 2 is approximately 30% higher than Option 1, based on the additional required RF power.

Option 1		**Option 2**	
Subsystem	**Cost ($M 2019)**	**Subsystem**	**Cost ($M 2019)**
RFQ (175 MHz)	11.28	RFQ (175 MHz)	11.28
SCRF HWR (175 MHz)	34.05	NC DTL (175 MHz)	32.82
RF Power	19.94	RF Power	26.15
Cryoplant	8.50		
Total	**73.76**	**Total**	**70.25**

An overall total order of magnitude accelerator cost can be estimated using the additional cost scaling information found in Table 18 and assuming a major accelerator system cost of $75M. The table below summarizes the results.

Subsystem	**Cost**	**Cost Scaling (2019$)**
Project Management	$7.5M	10% of total project cost
Design	$3.8M	5% of total project cost
Accelerator Systems- RFQ (includes LEBT), MEBT, Main Linac, RF Power, etc.	$75.0M	Cryoplant costs included in assumed $75M estimate independent of main linac type.
Instrumentation & Controls (IC)	$7.5M	10%-15% of accelerator equipment cost
Commissioning	$2.3M	3% of total project cost
As-Built Drawings & Documentation	$1.2M	1.5% of total project cost
Tooling	$3.0M	4% of total project cost
Total Accelerator Cost =	**$100.1M**	

Technology Readiness Summary

All accelerator technologies proposed, have in general, been successfully demonstrated in a relevant operational environment meeting mission requirements. As such, overall these technologies are TRL 9. The TRL levels as applied to generating a CW 125-mA D+ beam for the RFQ, NC DTL, and the SCRF linac are TRL 7, TRL 6, TRL 7, respectively. Only recently has an RFQ demonstrated operation at 125 mA, CW as required for the proposed D-Li Fusion Neutron Facility [19]. Further integration of this RFQ with a main linac and integrated operation of the full system will be required to reach the next TRL level. Likewise, operation of similar SCRF HWR-based linacs have been operated as full production systems, however not at the required power levels for fusion material testing. This places the SCRF technology as applied to a D-Li Fusion Neutron Facility at a slightly higher TRL level as compared to a high-power CW DTL. It should be noted that most technology development towards this accelerator application has been focused on SCRF linac technology and very little development effort has been devoted to development of a high-power NC CW DTL option. A particular bias noted by the IFMIF-EVEDA-LIPAc collaboration was the desire to develop advanced technologies such as SCRF accelerators, however, more conventional accelerator technology such as the NC DTL is most likely also viable, in particular using modern design tools, and potentially offers several advantages as are briefly discussed in the recommendations section below.

Recommendations

- The goal is to build a green-field D-Li Fusion Neutron Facility within 5 years at moderate cost. Since the total costs for both Options 1 and 2 (SCRF and NC, respectively) are essentially equivalent, other down-select criteria must be agreed upon such as simplicity of design, fabrication, and/or operation, radiation hardness, operating cost, etc.
- It is critical to select the most viable accelerator topology that is likely to meet both cost and schedule while allowing for reliable operation and hands-on maintenance.
- Consider a normal-conducting (NC) accelerator option for the main linac. This option has the following advantages over an alternative SCRF linac:
  - The NC DTL eliminates the inherent complexity of SCRF cavities – fabrication, assembly, and operation.
  - Fabrication of SCRF cavities may require using a foreign vendor to procure niobium.
  - A NC structure is inherently more rad hard and does not suffer from radiation-induced cavity quenching.
  - The NC DTL topology allows for the use of permanent magnet quadrupoles (PMQs) for transverse focusing that eliminates their associated heat loads and the need for magnet power supplies (for example, PMQs are used in the SNS DTL). A SCRF linac will require electromagnetic superconducting solenoids or quadrupoles, and their associated power supplies.
  - Use of a NC DTL eliminates most operational set points as compared to an SCRF-based linac and as a result, simplifies start-up and operation. This includes minimization of the number of RF stations that need RF phase and amplitude adjustments if an appropriate RF system topology is selected.
- Suggest considering the use of solid-state RF generators due to somewhat lower cost per watt, high reliability and modularization.
- Consider potential project partners:
  - LANL – RFQ, DTL, and/or RF systems

  - MSU/FRIB – RFQ, DTL, and/or SCRF HWR linac; the FRIB project is nearing completion and overall accelerator costs could be reduced due to low university overheads.
- If an SCRF-based linac option is selected, access to detailed design information from IFMIF/EVEDA would be advantageous and could shorten the design phase and reduce overall accelerator design costs. A partnership with MSU/FRIB could have the same outcome since senior staff at MSU did the SARAF design while at ANL.

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